REVOLUTIONIZING DOPPLER RADAR WITH RF-PHOTONICS

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ABSTRACT

We will discuss how to fundamentally improve radar systems by using RF-photonics in two ways: 1). Using a fiber-optic recirculation loop based interferoceiver to realize true correlation.[1] It is an optimum extra-wideband radar receiver capable of measuring Doppler beating with a single pulse. This eliminates Doppler range ambiguity. In addition, micro-Doppler signatures of any target become clearly recognizable for passive identification to prevent fratricide. 2). Further reduce the phase noise in an ultra-low-phase-noise opto-electronic oscillator (OEO) by eliminating RF amplifiers in the OEO loop to meet the requirement for low-speed Doppler detection and week signal detection.

1. INTRODUCTION

There has been no substantial change in the Doppler radar front-end architecture/concept since World-War II. The only difference in modern radar is the digital electronics used for signal processing. However, advances in that area can no longer improve the radar sensitivity since the signal to noise ratio has been set by the front-end hardware and the limitation in the traditional super-heterodyne receiver architecture. To fundamentally improve the radar system, one has to change the receiving architecture concept or improve front-end hardware. For the last two decades, many RF-photonic front-end architectures have been proposed, however, due to the immaturity of the RF-photonic link components and the system complexity, these RF-photonic systems could not meet the RF system requirements such as spur free dynamic range (SFDR), nor the cost requirement. Therefore, these RF-photonic approaches can not be considered for the realistic radar front-end yet. Recently, there have been significant performance improvements in the photonic components as the results of several DoD funded R&D programs and the development of the fiber telecom industry. Despite these improvements, there is still a shortfall of a few dB in the SFDR and other specifications. In this paper we introduce some new approaches that may not need the stringent requirements such as very large SFDR in the RF-photonic components to improve the Radar sensitivity.

One approach is to use a fiber-optic recirculation loop based interferoceiver to realize true correlation.[1] The low loss optical fiber loop can generate thousands of replicas from a single pulse which allows us to expand the original pulse signal in the time domain in order to extract additional phase information. It is not only the optimum radar receiver, but also an extra-wideband receiver, which is able to measure Doppler beating with a single input pulse. Current pulse Doppler radar has to receive multiple pulses in a relatively large time interval to be able to resolve the Doppler information with high spectral resolution. However, if the target changes its speed or trajectory during this time frame, the radar can no longer resolve the Doppler information. That is why the current Pulse Doppler radar can not resolve the micro-Doppler side band from the target's vibrational modes which are very important for target identification. With the RF-photonic interferoceiver, there would not be any Doppler range ambiguity and micro-Doppler signatures of any target become clearly recognizable for passive identification.

For Radar front-end hardware improvement, the most critical component is the oscillator. The phase noise of the oscillator increases exponentially near the carrier frequency. This noise is expressed in the received signals as clutter, especially in the urban environment. Current Doppler radar has difficulty detecting slow moving targets or targets with small cross-sections. The opto-electronic oscillator (OEO)[2] has shown promising ultra-low-phase-noise performance. The original OEO uses a long optical fiber as the high Q device to form a feed back loop. However, this type of OEO relies on an RF-filter to select the oscillation mode and an RF-amplifier as the

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gain element to sustain the oscillation. The RF-filter can not have large enough Q to filter out all the super-modes generated by the high Q fiber. These super-modes become the unwanted "spurs" of the RF system. Also, the phase noise generated by the RF-amplifier in the loop dominates the overall phase noise for the oscillator. Therefore there are many improvements which can be implemented for this type of OEO. Previously we have demonstrated an injection-locked dual OEO approach to eliminate the spurs.[3] In this paper we propose to further reduce the phase noise in an ultra-low-phase-noise OEO by eliminating RF amplifiers in the OEO loop, thereby meeting the requirement for low-speed Doppler detection and week signal detection.

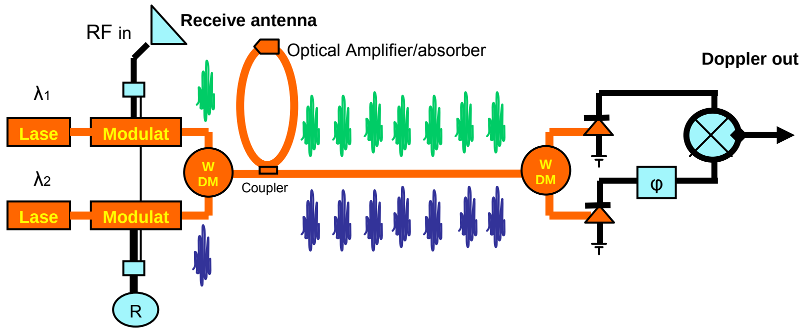

Fig.2. Block diagram of the optical fiber loop based pulse Doppler Radar receiver.

2. OPTICAL FIBER RECIRCULATION LOOP BASED INTERFEROCEIVER

The RF-photonic interferoceiver uses an optical fiber regeneration loop to replicate thousands of radar pulses that spread in the time domain from a single received Doppler-shifted radar pulse, then correlates these pulses with a train of reference pulses generated from an identical loop, thereby realizing a true correlation receiver as shown in Fig. 1. As a result, we will be able to resolve the Doppler information from a single radar pulse. This process catches an instant event from the target. Therefore it is possible to resolve micro-Doppler side bands of the target which allows us to identify the target through its vibrational Doppler side modes. In contrast, the current pulse-Doppler radar system has to rely on a train of transmitted/received pulses that bounced back from the target at different times to resolve the Doppler shift. As a result, the micro-Doppler information will be smeared.

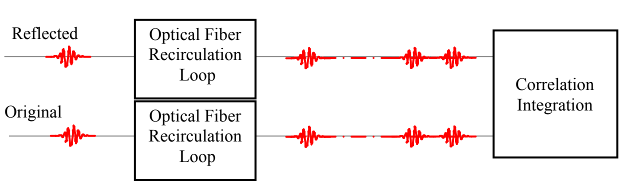

Fig.1. Block diagram of the optical fiber recirculation loop based true correlation receiver.

2.1. Theory and simulation

We have made our preliminary design of the optical fiber regeneration loop based interferoceiver system as shown in Fig.2, modeled and simulated the system for micro-Doppler detection. The system contains two RF-modulated optical inputs using two laser-modulator combinations with two laser wavelengths. A Doppler shifted RF pulse received at the antenna modulates the first laser of wavelength λ1 via optical modulator-1. At the same time, a reference RF pulse from a local oscillator modulates the second laser of wavelength λ2 via optical modulator-2. These two modulated optical pulses combine at an optical combiner and then, enter into a 2x2 optical coupler. The fiber-optic recirculation loop is formed with the 2x2 optical coupler so that each input pulse is split 50/50: one part going to the output port, while the other part goes to the recirculation loop. Therefore, at the output of the loop/coupler, a train of recirculated pulse pairs are generated. Theses replica pairs are separated by a WDM divider. A photodetector at the end of each output port of the WDM divider coverts the optical pulses back to RF pulses. Each RF-pulse pair can beat at a mixer connected with the photodetectors.

Even though the RF pulse replicas are generated by a single original input pulse, they are not identical in the time domain. Between each two neighboring recirculated pulses, there is a time delay caused by the one revolution travel time in the loop. Therefore, a phase evolution in time occurs in those pulses. At the RF mixer, when the recirculated Doppler shifted RF pulses beat with the reference RF pulses generated by the same recirculation loop, the Doppler frequency signal can be mapped as illustrated in Fig. 3. The detailed theoretical calculation for this process is published by Li in reference [1]. There are two major advantages in this Radar receiver architecture: First, the low loss fiber-optic loop can keep the pulse for a long period of time. For example using a few thousand recirculation pulses generated by a fiber loop of 10km or longer, we can cover a time frame near a second which will

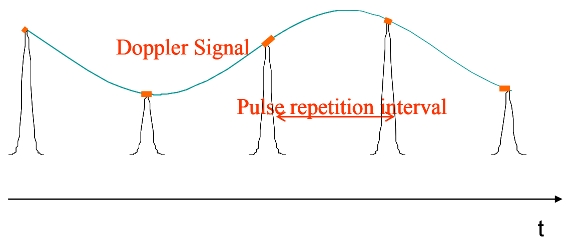

Fig.3. The Doppler signal can be obtained after the recirculated pulses pairs beat at the mixer.

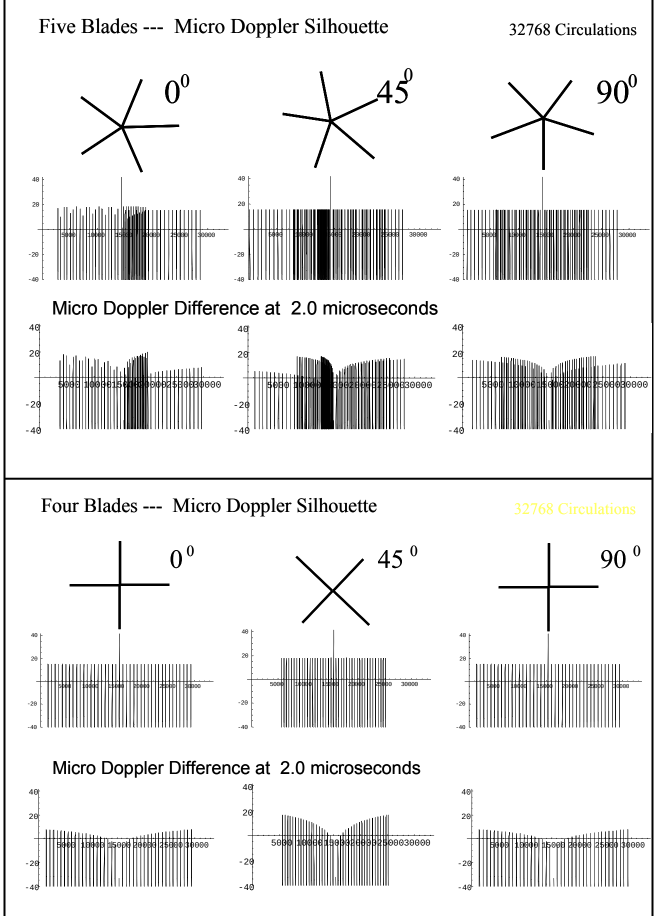

Fig. 4 . The calculated result of the micro-Dopplers from (A. Top) 4 blades helicopters; and (B. Bottom) 5 blades helicopters.

provide a spectral resolution near one Hz, therefore, micro-Doppler side-bands caused by the vibration mode of the target can be resolved from a signal original transit/receive pulse. This is equivalent to catching an instant picture from the target. This can never be done by the traditional pulse Doppler radar receiver which relies on taking multiple transmit/receive pulses to resolve the Doppler signal, because during the one second time frame, the target motion has changed which causes the principle Doppler and micro-Doppler side-bands' signal to be smeared in this radar receiver. Secondly, because the reference pulses are circulated in the same fiber-optic loop simultaneously, the noise generated by the loop may be coherent for both the Doppler shifted RF and reference RF pulse pair. Therefore one can eliminate this added noise easily with the mixer electronics.

To predict the Radar performance/sensitivity with this RF-photonic recirculation loop based interferoceiver, a simulation calculation has been done by adding some noise terms in the equations developed in reference [1]. We simulated two helicopters as target, one with 5 rotating helicopter blades, the other has 4 blades. The calculation uses a 30us delay loop for recirculating a few thousand to thirty thousand pulses. Figure 4 (A) and (B) show the calculated result of the micro-Dopplers from both 5 blades and 4 blades helicopters respectively. In order to make the comparison easier, we have also calculated the differential Doppler signal between 2 microseconds as shown in the Fig.4 (A) and (B). We can clearly distinguish the two helicopters.

2.2. Experiments

We have also experimentally investigated a simple optical fiber regeneration loop. Figure 5 shows the experimental set-up. A CW 1555 nm laser is fed through a high extinction ratio LiNbO3 Mach-Zender interferometer so as to produce a short (~25 μs) on-state pulse with a long (~11ms) off-state period. The pulse is split with a 2x2 coupler, sending half the power into the loop and half to a photodetector. The light within the loop is delayed by nL/c. Our loop was roughly 10 km in length, for a delay of about 50 μs per circuit. Upon completing each circuit, the pulse is split again, sending half the

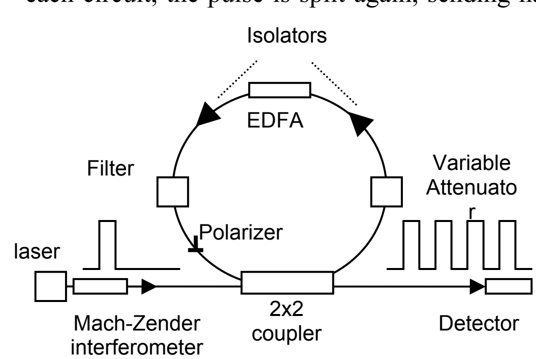

Figure 5. Fiber optic pulse regenerating loop

signal to the detector, and half back into the loop for another circuit. The cycle is repeated, producing a train of replicated pulses separated by the loop-transit time delay. Within the loop, it is necessary to incorporate several components. An erbium-doped fiber amplifier (EDFA) is used to amplify the signal which is reduced by 3 dB per circuit by the coupler, and an additional amount due to fiber and component loss. Because the coupler is sensitive to polarization effects, a polarization rotator is placed within the loop. Because the EDFA produces a broad spectrum of noise in addition to the desired signal, a filter is placed in the loop, reducing the amount of noise that is repetitively amplified. Isolators are placed before and after the amplifier to prevent the propagation of signals reflected from other components. A variable attenuator is placed before the amplifier (which is not variable) so that the optimum level of amplification can be applied.

A fiber-optic loop is a very good cavity device for applications using the resonance effect, but it is difficult to use it not for the cavity purpose and avoid the resonance. Ideally we want the EDFA to attain the optimum amplification level that compensates all the loss in the loop so that each out put pulse has the same amplitude. However, this will make the loop have enough gain that reaches the lasing condition so it is operating as a ring laser. Even before the loop lases, the EDFA may generate enough noise signal that is amplified with the loop cavity effect to destroy the pulse information, but without enough amplification the replicas drop off in amplitude exponentially so that not enough replicas are generated. Figure 6 shows the pulse train generated by the loop built by commercial photonic components. More than one hundred pulses have been generated. As shown in the data, the amplitude of each pulse generated is about 0.2dB lower than the previous one in the train. When we attempt to increase the gain in the loop, the loop lases.

There are several techniques to increase the number of pulses. First approach is to reduce the optical noise generated by the EDFA in the loop by investing in a low noise EDFA and using a narrower bandwidth optical filter. This will provide a very limited improvement. Besides, in our case two laser pulses with different wavelengths have to pass through the same filter. Secondly we have tried to add an optical path perturbation such as a modulated optical fiber stretcher in the loop to destroy the resonance cavity effect. However, we have some difficulty observing the output pulses using our digital sampling oscilloscope, because the period of the pulse train changes in time causing a synchronization problem for the scope. The next approach is to build a feed-back gain control circuit for the EDFA in the loop which may produce few thousand pulses.[2] Beyond a few thousand pulses, more sophisticated techniques such as EDFA gain clamping[3] and Semiconductor Laser Amplifier in a Loop Mirror (SLALOM)[4]. SLALOM techniques have been reported to produce millions of pulses. However, this technique may not be suitable in our case that requires us to maintain the integrity of the RF signal carried by the optical pulses.

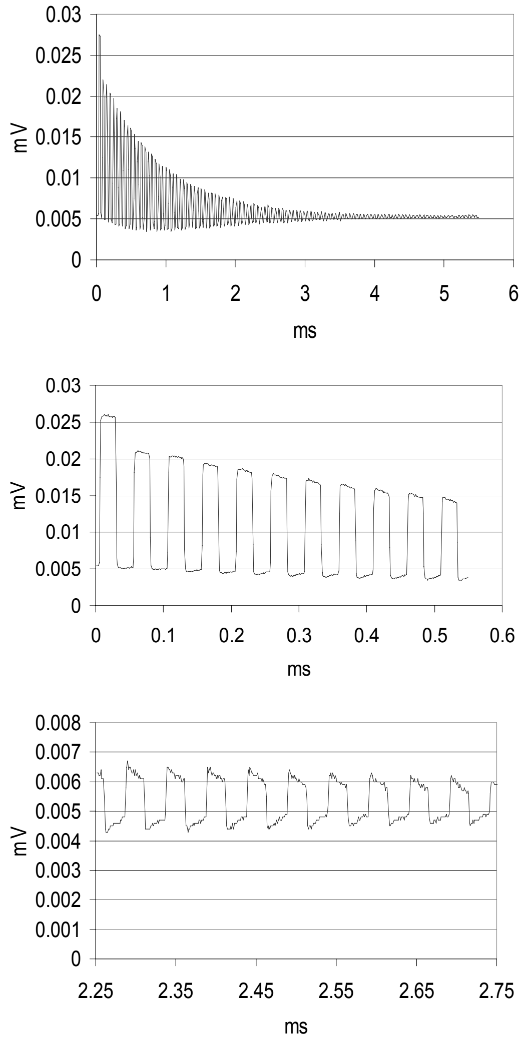

Figure 6. From top to bottom, (a. top) the full pulse train, (b. middle) the first 10 pulses, expanded, (c. bottom) expanded around the 50^{th} pulse

3. IMPROVED OPTOELECTRONIC OSCILLATOR

The most hardware improvement RF-Photonics can offer now is the ultra-low-phase-noise OEO built by a high-Q optical system such as a long optical fiber. Reduction of the phase noise can directly increase the Radar sensitivity. It has been demonstrated that the low phase noise level near the carrier frequency (10-100Hz offset range) of the OEO meets the requirement for low-speed Doppler detection. The OEO also has the advantage of low vibration sensitivity, frequency agility, and low cost compared with other precision oscillators. The original OEO used a long optical fiber as a delay line in a feedback loop of optical and electronic paths.[5] The basic concept is to convert microwave oscillations into modulated laser light and send it in a long wound optical fiber. At the other end of the fiber a photodetector converts the modulated light signal back into microwave signals which are amplified and filtered by a microwave filter, which in turn is fed into the optical modulator, closing the feedback loop. Several kilometers of low loss optical fiber in the OEO loop can generate a cavity with Q values higher than 10^9, which is several orders of magnitude higher than that from the best commercial microwave filters. In the OEO, the mode spacing is inversely proportional to the resonator delay, therefore, the RF filter is not able to filter out many of the unwanted modes which become "spurs" for the RF-system.

3.1. Reduce Spurious Level with Injection Locked Dual OEO

We have designed an injection-locked dual-OEO system that essentially eliminates the spurs.[6] However, it was a laboratory proto-type demonstration that requires precise manual tuning to keep the injection lock with lower spurious level. To make this OEO field-able, we need to develop an electronic feed back servo system that can automatically tune the injection locked dual OEO to keep it in the desired operation status. For this we have to investigate the injection-locking mechanism and how it relates the spurs-level and the system Q. Figure 7. shows one of the injection-locked dual OEO system configurations. The RF output signal from a high-Q long-fiber single-loop master OEO is injected into a short fiber slave OEO and lock the oscillation frequency and its phase. The length of the slave OEO's optical fiber is chosen such that only one mode is allowed to pass within the RF-filter bandwidth. The master OEO's long fiber produces the necessary high Q and the slave short loop OEO filter out the spurs. We are making a systematic study by change the system configuration such as the injection position where the mast-OEO signal is input into the slave OEO, the power injection ratios such as the relative amount of master OEO's RF signal injected in to the slave OEO. Since the commercial RF directional coupler has always small amount of leakage in the revise direction, there is small amount

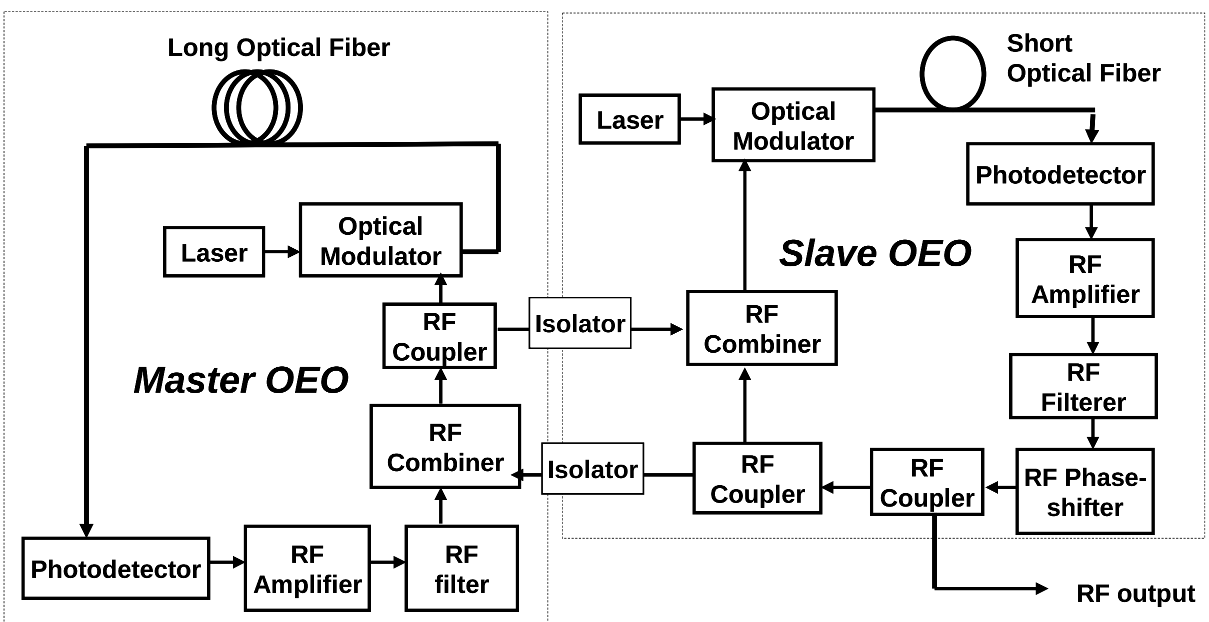

Fig. 7. Block diagram of an injection-locked dual Opto-Electronic Oscillator for experimental study.

of signal from the slave OEO back injected into the master OEO. We found out this back injection plays an important role in reducing the spurs, however it may hurt the system Q. Therefore we have also studied the ratio of this back injection with respect to the forward injection level. A large amount of data was taken from these systematic studies. Based on these data we can design the electronic feed back servo system for the automatic oscillator control.

3.2. Reduce the Phase Noise Level by Elimination the RF-Amplifiers in the OEO

The next step is to further reduce the phase noise. Currently we are working on further reduction of the phase noise in the intermediate offset frequency range (0.1-10kHz). The noise in this frequency range is dominated by the RF-amplifiers in the OEO loop.[7] Recently, several high performance photonic components such as low Vpi optical modulators, narrow line-width high power lasers, and high power photodetectors were developed (by DARPA RF-Photonic programs) which can produce a highly efficient RF-Photonic link that gives RF-gain instead of loss. That may allow us to eliminate the RF-amplifiers in the OEO loop as shown in Fig.8, thereby reducing the phase noise. The modulator is

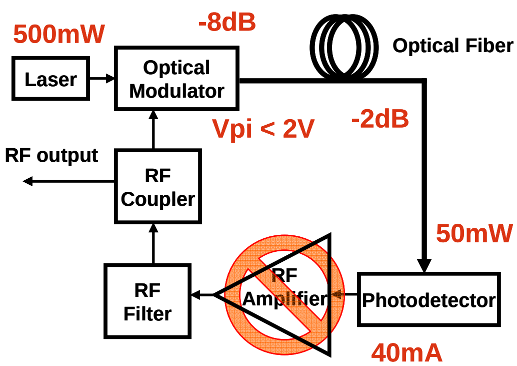

Fig. 8. Eliminating the RF-amplifier in the OEO loop.

the critical part for obtaining the link gain. We use a LiNbO3 Mach-Zehnder modulator made by EO-Space that has Vpi <2V and insertion loss <8dB. The insertion loss of the optical fiber and the connectors is about 2 dB. If we provide 500mW laser power, that will give the photodetector up to 50mW optical input which may produce ~40mA RF current to modulate the optical modulator without an RF amplifier. However, when we use commercial RF-Photonic link components with ~20dB RF link loss in an OEO we need a 40 to 50 dB gain RF-amplifier to start the oscillation. Therefore, there is additional loss in the loop. Part of this loss is from the RF-components (filter coupler, etc). The other part may be due to the dispersion in the fiber link. Although, we can increase the laser power, that will cause an undesired Brilloin scattering problem in the fiber. The better way is to reduce the dispersion by using a narrow linewidth laser. Once we can eliminate the RF-amplifier in the OEO loop. The next most significant phase noise contributor will be the laser's Relative Intensity Noise (RIN). Therefore, a low RIN, narrow line-width and high power laser is also needed to reduce the OEO phase noise.

CONCLUSIONS

We propose two ways to fundamentally improve the Radar performance and increase Radar detection capability by using RF-photonic technologies that are mature enough for commercialization in the near future. One is the fiber-optic loop based inteferoceiver for Radar receiver that will be capable to identify the target through micro-Doppler detection. The second is an ultra-low phase noise opto-electronic oscillator. This OEO will allow the detection of slow moving targets.

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